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by

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Abstract

Undesirable consequences of dangerous goods incidents can be mitigated by quick arrival of specialized response teams at the accident site. We present a novel methodology to determine the optimal design of a specialized team network so as to maximize its ability to respond to such incidents in a region. We show that this problem can be represented via a maximal arc-covering model. We devise a Branch and Bound procedure to solve the arising non-linear integer program. Our solution procedure proved computationally efficient on randomly generated large-scale problem instances. The proposed methodology is applied to assess the emergency response capability to transport incidents that involve gasoline, in Québec and Ontario. We point out the possibility of a significant improvement via relocation of the existing specialized teams, which are currently stationed at the shipment origins.

Key words: hazardous materials, transportation, emergency response, maximal cover, geographical information systems.

Résumé

Les conséquences néfastes d'incidents impliquant des matières dangereuses peuvent être amoindries par l'arrivée rapide d'un groupe d'intervention spécialisé sur le site de l'accident. Nous présentons une méthodologie originale pour déterminer la conception optimale d'un réseau d'équipes spécialisées afin de maximiser leur capacité à répondre à de tels incidents dans une région. Nous montrons que ce problème peut être représenté par un modèle de maximisation de couverture des arcs. Nous proposons une procédure de séparation et évaluation progressive pour résoudre le programme en nombres entiers non linéaire résultant. Notre méthode de résolution s'est montrée efficace en termes de calcul sur des instances de grande taille engendrées au hasard. Nous appliquons la méthodologie proposée pour évaluer les capacités d'intervention d'urgence en réponse à des incidents de transport impliquant de l'essence au Québec et en Ontario. Nous soulignons la possibilité d'une amélioration notable de ces capacités par la relocalisation des équipes spécialisées existantes qui sont actuellement placées aux points d'origine des chargements.

Mots clés : matières dangereuses, transport, intervention d'urgence, maximisation de couverture, système à référence spatiale.

1 Introduction

A substantial amount of hazardous materials (hazmats), such as flammable liquids and poisonous gases, need to be transported prior to their consumption or disposal. U.S. Department of Transportation (2000), for example, estimates that there were 300 million dangerous goods shipments in 1998 and forecasts a 2% annual growth in the amount of hazmats produced in the country. Despite widespread deregulation of transport industry, mitigation of the public and environmental risks associated with these shipments remains as a government responsibility. A number of transport safety measures aim at reducing the likelihood and possible undesirable consequences of incidents involving accidental release of dangerous goods during transportation. This proactive group of policy tools includes the use of low-risk routes for hazmat shipments, regulatory requirements for driver training, driving hours and container specifications, inspections to enforce compliance, and closure of certain road segments to vehicles carrying dangerous goods. Nonetheless, accidents do happen. During the 1990-98 period, for example, there were an average of 410 serious hazmat incidents in the U.S. annually, which caused fatalities, injuries, evacuation of homes and businesses as well as property damage (U.S. Department of Transportation, 2000). When a hazmat incident occurs, effective emergency response is crucial for containing its impact to the smallest possible area around the accident site. Clearly, such reactive safety measures complement the proactive policies in mitigating undesirable consequences of transport incidents. The establishment of a hazmat emergency response system, which is the focus of this paper, constitutes a building block toward a comprehensive public and environmental safety infrastructure.

The firefighters, ambulances and police in the vicinity of accident site are typically first to respond to a transport accident. It is important that they quickly identify the type of hazmat involved (if any) in the incident and take precautions to protect the general public during the initial response phase. To facilitate this, U.S., Canada and Mexico require each potentially hazardous vehicle to carry a placard indicating the type (4-digit ID number) of its cargo. Also, a guidebook is developed jointly by the three transport ministries to aid the first-responders e.g., the area to be evacuated depending on hazmat type and the size of spill (Transport Canada, 2000). In most cases, however, it is necessary to send a specialized

hazmat response team and equipment to the accident site. It is crucial that the availability and involvement of such specialized teams are planned prior to dangerous goods shipments. In Canada, the 1992 Transportation of Dangerous Goods Act, in fact, requires each shipper to have an approved emergency response assistance plan (ERAP) before transporting or importing dangerous goods. An ERAP must provide a description of the arrangements for specialized emergency response, a potential accident assessment as well as a contact person the first-responders need to call to activate the plan. The final phase of emergency response to hazmat incidents is the cleanup of accident site, which is usually overseen by an environmental protection agency with jurisdiction.

The current practice and regulation of dangerous goods emergency response emphasize the availability of information, the coordination among responders and the procedures that need to be followed at the accident site. The time it takes for the specialized response team to arrive at the accident site is another crucial factor, which seems to be overlooked by regulators. In Canada, for example, there are no established response time standards that are used by Transport Canada in the approval process of ERAPs (Lapalme, 2003). The importance of quick response in alleviating undesirable consequences of hazmat incidents, however, has been recognized in a number of occasions. One example is the 1998 derailment of a CSX freight train in West Virginia that resulted in the release of 21,500 gallons of formaldehyde solution from two railcars. In a safety recommendation report following this accident, U.S. National Transportation Safety Board (1999) stated that the three-hour delay in the arrival of specialized teams could have had serious consequences had the leaking chemicals been more hazardous than formaldehyde. A recent report by the same agency recommended the inclusion of railroad mileposts in emergency response maps throughout the U.S. so as to minimize response times (U.S. National Transportation Safety Board, 2001). In January 2002, North Dakota governor highlighted the fast response of emergency management teams to a Canadian Pacific Railway train derailment as the main factor that kept the damage caused by this spectacular accident[1] relatively low (Minot Daily News, 2002).

In this paper, we provide a methodology for determining the optimal locations of special-

[1] 240,000 gallons of anhydrous ammonia were released from eight ruptured tank-cars.

ized response team stations so as to maximize their ability to respond to hazmat incidents within a threshold time. We assume that the number of stations to be established and their service region are pre-determined. The required equipment, expertise and response time varies with the type of dangerous good involved in the incident. Therefore, a separate emergency response station network needs to be established for each hazmat type that is shipped in high volumes across a region. The concept of location coverage is pertinent for representing the objective of our problem. If a potential incident site can be reached from one of the emergency response stations within the threshold time, then this location is considered covered. Note that the incident can occur anywhere on the transport network used for dangerous goods shipments. The number of specialized teams is often insufficient to cover the entire transport network and the road links with higher risk need to be prioritized. In a critical overview, Erkut and Verter (1998) identify population exposure[2], incident probability and expected risk (i.e., probability times exposure) as the prevailing models for hazmat transport risk. These risk attributes determine the relative significance of providing emergency response coverage to each road link.

The hazmat emergency response network design problem can be solved via a maximal arc-covering location model. This is an extension of the maximal covering location model, which has been used in siting non-hazmat emergency services such as fire stations, ambulance stations and blood banks.[3] The original model, developed by Church and ReVelle (1974), seeks to maximize the coverage provided to a set of demand points each corresponding to a population center. Point coverage has remained as a common structural property of the numerous extensions proposed within the past three decades. We refer the reader to Marianov and Serra (2002) for a recent review of this literature. The distinguishing feature of hazmat emergency response is that it requires coverage of a set of arcs that make up the transport network rather than a set of points. As we will show, the resulting problem is a non-linear integer program that is difficult to solve. We present an efficient Branch and Bound procedure to solve this problem. We are unaware of any previous work on the

[2]The number of people within a threshold distance of the road link times the number of hazmat trucks shipped across the link.

[3]See Verter and Lapierre (2002) for references.

maximal arc-covering location model.

The remainder of the paper is organized as follows. Section 2 provides a formal definition of the problem and its analytical properties. Section 3 presents a mathematical programming formulation and outlines a Branch and Bound procedure for solving the problem. We report on computational performance of the proposed solution algorithm in Section 4. An application of our methodology for designing an emergency response system to gasoline incidents in Quebec and Ontario highways is presented in Section 5. Section 6 provides our concluding comments.

2 The Problem

Let $G = (N, A)$ be a network with a nodal set N and an arc set A. Associated with each arc (i, j) there is a weight w_{ij} which represents the benefit of covering entirely arc $(i, j) \in A$. Let d_{ij} designate the length of arc (i, j) and $d(x, y)$ the shortest distance between any pair of points $x, y \in G$. We denote by p the number of (response) facilities to be located on the network.

The maximal arc covering problem involves locating p facilities so as to maximize the total weighted arc length covered. A point $y \in G$ is covered by a facility at $x \in G$ if $d(x, y) \leq R$, where R is the pre-determined coverage distance. Let $Z_{kl}(S)$ denote the fraction of arc $(k, l) \in A$ covered by a set of facilities located at $S \subseteq G$ (i.e., $0 \leq Z_{kl}(S) \leq 1$). Thus, the problem is

$$\max_{\substack{S \subseteq G \\ |S|=p}} w(S) = \sum_{(k,l) \in A} w_{kl} Z_{kl}(S) \tag{1}$$

Let $S = \{j\}$ and $p = 1$. Let $a_{kl}(j)$ represent the fraction of arc (k, l) covered by the facility at j through node k.

$$a_{kl}(j) = \begin{cases} 1 & \text{if } d(j,k) + d_{kl} \leq R \\ \frac{R - d(j,k)}{d_{kl}} & \text{if } d(j,k) \leq R < d(j,k) + d_{kl} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

We denote the fraction of coverage provided by facility j via node l as $a_{lk}(j)$, which can

be computed by replacing $d(j,k)$ with $d(j,l)$ in (2). Clearly, the total coverage of arc (k,l) by facility j cannot exceed 100%, and hence

$$Z_{kl}(j) = \min\{a_{kl}(j) + a_{lk}(j), 1\}. \tag{3}$$

The intention in (3) is to avoid double counting arc coverage.

As an example let us refer to the simple 3-node network depicted in Figure 1 where lengths of arcs are the numbers next to the arcs. It is very easy to verify that if j is node 1 and $(k,l) = (2,3)$ then: when $R = 9$, $Z_{23}(1) = \min\{1+1, 1\} = 1$; when $R = 7$, $Z_{23}(1) = \min\{\frac{4}{5}+\frac{3}{5}, 1\} = 1$; when $R = 5$, $Z_{23}(1) = \min\{\frac{2}{5}+\frac{1}{5}, 1\} = \frac{3}{5}$; when $R = 3.5$, $Z_{23}(1) = \{\frac{5}{5} + 0, 1\} = .1$ and when $R = 2$, $Z_{23}(1) = 0$.

----------**Insert Figure 1 here**----------

The above method for computing arc coverage can be extended to $S = \{x_1, x_2, \ldots, x_p\}$. When there are p facilities, we need to take into account the maximum coverage through nodes k and l. Thus,

$$Z_{kl}(S) = \min\left\{\max_{j=1,\ldots,p} a_{kl}(x_j) + \max_{j=1,\ldots,p} a_{lk}(x_j), 1\right\} \tag{4}$$

It is possible that different facilities provide the maximum coverage through the two end nodes of arc (k,l). Again, (4) ensures that there is no double counting of coverage. For the example in Figure 1, if x_1 is node 1 and x_2 is a point at distance 1 from node 1 on link $(1,2)$ and $R = 5$, then

$$Z_{23}(x_1, x_2) = \min\left\{\max\left\{\frac{2}{5}, \frac{3}{5}\right\} + \max\left\{\frac{1}{5}, 0\right\}, 1\right\} = \frac{4}{5}.$$

Let us denote by $N(R)$ the set of all points on the network that are at a distance R from any location in N. Let $\bar{N} = N \cup N(R)$.

Theorem 1: *An optimal set of location exists in* $\bar{N}$.

Proof: Let $S^* = \{x_1, x_2, \ldots, x_p\}$ be an optimal set of location and suppose that x_f is a point on some arc $(a,b) \in A$ and $x_f \notin \bar{N}$. Let y_1 and y_2 be the closest two points in $\bar{N}$ to

x_f respectively in the direction of a and b. Obviously $y_1, y_2 \in (a, b)$. We can express $W(S^*)$ (see expression (1)) as follows:

$$W(S^*) = \sum_{(k,l)\in A(x_f)} w_{kl} Z_{kl}(S^*) + C_1 \tag{5}$$

where $A(x_f)$ is the set of all arcs for which either one of the maximums in expression (4) is attained at x_f (ties are broken arbitrarily), and

$$C_1 = \sum_{(k,l)\in A - A(x_f)} w_{kl} Z_{kl}(S^*)$$

$W(S^*)$ can be re-written as follows:

$$\begin{aligned} W(S^*) &= \sum_{(k,l)\in A^1(x_f)} w_{kl} \min\{a_{kl}(x_f) + C^2_{kl}, 1\} + \sum_{(k,l)\in A^2(x_f)} w_{kl} \min\{C^1_{kl} + a_{lk}(x_f), 1\} \\ &+ \sum_{(k,l)\in A^{12}(x_f)} w_{kl} \min\{a_{kl}(x_f) + a_{lk}(x_f), 1\} + C_1 \end{aligned} \tag{6}$$

where

$$A^1(x_f) = \{(k,l) \in A(x_f); \arg(\max_{j=1,\ldots,p} a_{kl}(x_j)) = x_f \text{ and } \arg\left(\max_{j=1,\ldots,p} a_{lk}(x_f)\right) \neq x_f\}$$

$$A^2(x_f) = \{(k,l) \in A(x_f); \arg(\max_{j=1,\ldots,p} a_{kl}(x_j)) \neq x_f \text{ and } \arg\left(\max_{j=1,\ldots,p} a_{lk}(x_j)\right) = x_f\}$$

$$A^{12}(x_f) = \{(k,l) \in A(x_f); \arg(\max_{j=1,\ldots,p} a_{kl}(x_j)) = \arg\left(\max_{j=1,\ldots,p} a_{lk}(x_j)\right) = x_f\}$$

$$C^1_{kl} = \max_{\substack{j=1,\ldots,p \\ j\neq x_f}} a_{kl}(x_j)$$

$$C^2_{kl} = \max_{\substack{j=1,\ldots,p \\ j\neq x_f}} a_{lk}(x_j)$$

Notice that $a_{kl}(x_j)$, $a_{lk}(x_j)$ are all constants or linear functions of x_f and C^1_{kl}, C^2_{kl} are all constants as functions of x_f. Moreover, even though each one of the minimums in (6) may be piecewise concave function of x_f, in $[y_1, y_2]$ it is either the constant 1 or a linear function of x_f. Therefore $W(S^*)$ is a linear function of x_f and thus either y_1 or y_2 must be at least as good as x_f. □

Since $\bar{N}$ is a finite set we can assume without loss of generality (for the sake of the rest of our discussion) that $\bar{N} = N$.

3 Solving the Problem

We now formulate our problem as a mathematical program (P). Let us define two sets of decision variables y_j, $j \in N$ and Z_{kl}, $(k,l) \in A$ as follows:

$y_j = 1$ if a facility is located at node j, 0 otherwise,

Z_{kl} = fraction of arc (k,l) covered.

We also define parameters $a_{jkl} \quad j \in N \quad (k,l) \in A$ as the fraction of arc (k,l) covered by a facility located at node j through node k. Therefore a_{jkl} is identical to $a_{kl}(j)$ and a_{jlk} is identical to $a_{lk}(j)$ defined earlier. We can now formulate problem (P).

$$\text{maximize} \sum_{(k,l)\in A} w_{kl} Z_{kl}$$

(P) $s.t.$

$$\sum_{j\in N} y_j = p \tag{7}$$

$$\max_{j\in N}\{y_j a_{jkl}\} + \max_{j\in N}\{y_j a_{jlk}\} \geq Z_{kl} \qquad (k,l) \in A \tag{8}$$

$$0 \leq Z_{kl} \leq 1 \qquad (k,l) \in A \tag{9}$$

$$y_j = 0,1 \qquad j \in N \tag{10}$$

Constraint (7) limits the number of facilities to p. Together with the objective function, constraints (8) ensure that Z_{kl} represents the total coverage provided to arc (k,l) through nodes k and l. Note that $Z_{kl} = 0$ unless there are facilities that cover arc (k,l). Also, (8) and (9) eliminate double-counting of any coverage overlap among k and l. Problem (P) is a mixed integer non-linear program, which we solve using Branch and Bound. To obtain an upper bound, we solve the (LP) relaxation of a new problem called (P′).

$$\max \sum_{(k,l)\in A} w_{kl} Z_{kl}$$

(P′) $s.t.$

$$\sum_{j\in N} y_j = p$$

$$\sum_{j\in N} y_j \min(a_{jkl} + a_{jlk}, 1) \geq Z_{kl} \qquad (k,l) \in A \tag{11}$$

Node	Arcs (k,l) and (l,k)													
	(1,2)	(2,1)	(1,5)	(5,1)	(1,4)	(4,1)	(2,5)	(5,2)	(2,3)	(3,2)	(3,5)	(5,3)	(4,5)	(5,4)
1	1	1	1	0	1	1	$\frac{1}{3}$	0	$\frac{1}{4}$	0	0	0	1	0
2	1	1	$\frac{1}{2}$	0	1	0	$\frac{2}{3}$	0	$\frac{1}{2}$	0	0	0	0	0
3	0	0	0	$\frac{1}{2}$	0	0	0	$\frac{1}{3}$	0	$\frac{1}{2}$	1	1	0	1
4	1	0	$\frac{1}{2}$	$\frac{1}{2}$	1	1	0	$\frac{1}{3}$	0	0	0	1	1	1
5	0	0	0	1	0	1	0	$\frac{2}{3}$	0	$\frac{1}{4}$	1	1	1	1

Table 1: a_{jkl} and a_{jlk} Values for the Example

$$0 \leq Z_{kl} \leq 1 \qquad (k,l) \in A$$

$$y_j = 0,1 \qquad j \in N$$

Problems (P′) and (P) are identical except for constraints (8) and (11). It is easy to verify that any solution that is feasible in (P) is also feasible in (P′) and therefore (P′) and certainly the (LP) relaxation of (P′) provides an upper bound for (P). Constraint (11), in fact, overestimates Z_{kl} by double-counting the coverage provided by different facilities. To illustrate, take two facilities $i, j \in N$ and arc $(k,l) \in A$, where $d_{kl} = 10$, $d(i,k) = 7$ and $d(j,k) = 5$. When coverage distance $R = 8$, $a_{ikl} = 0.1$ and $a_{jkl} = 0.3$. In this example, the actual coverage of arc (k,l) through k is 0.3, whereas adding up the coverage provided by nodes i and j as in (11) estimates the coverage as 0.4.

Notice that if the optimal solution of (P′) contains only integer values of the y_j variables then we can calculate $Z_{kl}(S)$, where S is the set of the p y_j variables equal to 1, using (4) and $w(S)$ using (1) and obtain a feasible solution to (P) that may serve as the lower bound.

As an example of the discussion above let us refer to the 5-node network in Figure 2 with $R = 2$ and $w_{kl} = 1$ for $k, l \in N$. The parameters a_{jkl} and a_{jlk} are summarized in Table 1. Suppose $p = 2$.

————Insert Figure 2 here————

We first solve the problem by enumerating all possible solutions. In Table 2 we summarize the coverage $Z_{kl}(S)$ for all $(k,l) \in A$ and the objective function value for all possible locations (pairs). From Table 2, $S^* = \{2,3\}$ is the optimal solution with objective function value 7.

Arc	Locations (Pairs)									
	1,2	1,3	1,4	1,5	2,3	2,4	2,5	3,4	3,5	4,5
(1,2)	1	1	1	1	1	1	1	1	0	1
(1,5)	1	1	1	1	1	1	1	1	1	1
(1,4)	1	1	1	1	1	1	1	1	1	1
(2,5)	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	1	1	1	1	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
(2,3)	$\frac{1}{2}$	$\frac{3}{4}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{2}$	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$
(3,5)	0	1	1	1	1	1	1	1	1	1
(4,5)	1	1	1	1	1	1	1	1	1	1
$W(S)$	5.16	6.42	5.92	6.5	7	6.5	6.75	5.83	5.16	5.92

Table 2: $Z_{kl}(S)$ and $W(S)$ for All Locations

In the Branch and Bound tree we branch on the y_j values in lexicographic order based on subscript j. There are two branches for each node branched; one for $y_j = 1$ and one for $y_j = 0$. We solve the LP relaxation of (P′) at each node, where all decision variables in the partial solution are fixed. This provides an upper bound and if all the y_j variables are integers, we also obtain a feasible solution to (P) that may serve as the lower bound. The value of (1) for the solution of (P′) constitutes the initial lower bound at the root node of the Branch and Bound. A node is fathomed if either (i), the current lower bound is equal to or greater than the upper bound associated with the node, or (ii), the number of decision variables y_j fixed at 1 in the partial solution is equal to p –in this case the objective function value using (1) is compared to that of the lower bound for possible improvement. As mentioned above also, when the optimal solution to a nodal problem comprises integer y_j values we may improve the lower bound. In the remainder of the section we show an example of our basic Branch and Bound method. In the next section we elaborate more on some additional features of the Branch and Bound method.

Let us refer again to the network in Figure 2. The initial upper bound (UB) obtained with the (LP) relaxation (P′) is 7 (achieved for $y_2 = 1, y_3 = 1, y_j = 0$ otherwise, or $S = \{2,3\}$). Using (4) and (1) with $S = \{2,3\}$ we can verify that $W(S) = 7$ and thus the lower bound and upper bound are equal and thus $S = \{2,3\}$ is optimal. To be able to show a Branch and

Bound tree, suppose that we start with a lower bound of 6.5 obtained with the arbitrarily selected solution, $y_2 = y_4 = 1, y_j = 0$ otherwise.

The Branch and Bound tree is depicted in Figure 3. At node 3 the upper bound is calculated using the LP relaxation of (P′) with the additional constraints $y_1 = 0$. The upper bound is 7.0 achieved for $y_2 = y_3 = 1, y_j = 0$ otherwise. As discussed above, this solution provides a lower bound of 7 and therefore both nodes 2 and 3 are fathomed and $y_2 = 1, y_3 = 1$ is the optimal solution.

----------Insert Figure 3 here----------

4 Computational Experiments

Before moving on to a real-life application, the proposed algorithm was tested on 210 randomly generated problem instances. The objective of the computational experiments was two-fold: (*i*) to identify how problem parameters impact the required computational effort, and (*ii*) to determine whether the algorithm can be used to tackle large-scale problems. The Branch and Bound procedure is implemented in C and CPLEX 7.1 is used for solving the relaxed problem (P′) at each node of the tree. An important feature of our implementation is that the LPs at each node are not solved from scratch. Note that each problem is generated by adding a constraint to the problem at the preceding node. We use the solution from the preceding node in CPLEX as a starting solution to speed up the computation time. The computations were carried out on a SUN HPC4500 workstation. First, medium-size problems with up to 50 nodes and close to 500 arcs were solved. Then, the insights from these experiments were utilized in tackling large-scale instances of the problem with up to 150 nodes and 300 arcs. In this section, we report on our findings.

The medium-size problems comprise four sets based on the number of nodes i.e., $|N| = 20, 30, 40,$ and 50. For each set, five distinct networks were generated by deriving the number of arcs $|A|$ from a uniform distribution between $|N|$ and $10|N|$. In order to ensure connectivity, we first randomly generated a tree with $|N|$ nodes and then randomly added the remaining arcs to the network. The length of each arc d_{ij} is derived from a uniform

	p		
R	2	3	5
3	0.01	0.11	1.79
7	0.46	2.7	68.9
10	0.56	6.29	241.53

Table 3: CPU times in second for a (30, 76) network

distribution in the interval [1, 10], and $w_{ij} = 1$ for all arcs.[4] We solved nine instances of the problem for each network by varying the number of response facilities to be located and the coverage distance i.e., p and R. Three values were used for each of these two parameters. The p values are $\lceil\ i\ |N|\ \rceil$ for $i = 5\%,\ 10\%,$ and 15%.[5] The R values are $\lceil\ k(L_1 + L_2)\ \rceil$ for $k = \frac{1}{6},\ \frac{1}{3},$ and $\frac{1}{2}$, where $L1$ and $L2$ are the minimum and maximum path lengths in the node-to-node shortest path matrix.[6] Thus, a total of 180 instances were solved in the first phase.

For illustrative purposes, we first focus on the set of problems with $|N| = 30$. *Network #5* in this set has 76 arcs, where $L_2 = 19$ and $L_1 = 1$. CPU times for the nine instances of *Network #5* are depicted in Table 3. The average solution time for these nine problem instances is 35.8 seconds. The instance with highest p and R values ($p = 5$ and $R = 10$) requires the longest CPU time of 4.02 minutes. All 76 arcs are fully covered by the 5 facilities at optimal solution of this instance i.e., $w(S^*) = 76$. Although the objective function value of the feasible solution at the root node of Branch and Bound is 75.36, identifying the optimal solution involves 42,590 nodal problems. The dramatic increase in the CPU time as p increases is evident in Table 3. Notice that the required computational effort also increases exponentially with R. We do not report on solution details of the other problem sets for the sake of brevity. Nonetheless, we observed the same trends with regards to the impact of p and R on problem complexity.

The number of arcs is also a key driver of CPU time. For example, *Network #3* is the

[4]Variability in the benefit of covering each arc is incorporated in the next section.

[5]$\lceil . \rceil$ denotes upper ceiling.

[6]Each response team will presumably use the shortest path to reach the accident site from its facility.

most dense among the five 30-node networks we generated. The nine instances associated with this 226-arc network require an average of 5.95 minutes. The most challenging instance of *Network #3* took 34.8 minutes, which corresponds to the longest time required by the 45 30-node problems we solved. The impact of network density is also evident from Table 4, which depicts a summary of our computational experiments with medium-size problems. We imposed a limit of 750,000 on the number of nodes evaluated during Branch and Bound. In Table 4, "# Solved" indicates the number of instances that were solved to optimality within this limit (out of 9 instances). Clearly, the four instances of 40-node problems and the nine instances of 50-node problems that were terminated correspond to the networks with largest number of arcs. For these instances, processing 750,000 Branch and Bound nodes took about 5 hours of CPU time. The average CPU times of the proposed algorithm (until termination) for each problem set are depicted in Table 4. One of the key features of our algorithm is the quality of the upper bound provided at the root note. In Table 4, "UB Ratio" denotes the average of the ratios of optimal solution to initial upper bound for the problem instances in each set.[7] On the average, the optimal solution is always within 90% of the initial upper bound, which shows the high efficiency of our Branch and Bound scheme.

Before moving on to the large-scale problems with $|N| = 75, 100$, and 150, it is important to point out that some of the networks we tackled in the first-phase are quite dense. For example, *Network #1* in the $|N| = 50$ set has 446 arcs that amount to an average of nine links associated with each node. This level of network density is extremely rare in road networks, and hence we fixed the number of arcs as $2|N|$ for the larger networks in the second phase. We randomly generated five networks for each value of $|N|$ in this group. We also fixed $p = 5$ and solved two instances for each network with $R = \lceil\, k(L_1 + L_2)\,\rceil$ for $k = \frac{1}{6}$ and $\frac{1}{3}$. Table 5 provides a summary of our computational results with the large-scale problems. We solved all of the 75-node problems to optimality, whereas one 100-node instance and three 150-node instances were terminated due to the limit on the number of nodes in the Branch and Bound tree. All the terminated instances correspond to the larger coverage distance values. The 100-node instance took 5.27 hours to process 750,000 nodes. In order to keep the CPU times around 5 hours, however, the limit was reduced to 300,000 nodes for the 150-node problems.

[7]The instances that were not solved to optimality are not included in the "UB Ratio" calculations.

	Network #1	*Network #2*	*Network #3*	*Network #4*	*Network #5*
20-nodes					
# of arcs	50	146	31	113	75
L2 (km.)	17	7	29	9	12
# Solved	9	9	9	9	9
CPU (sec.)	0.28	0.91	0.11	0.82	0.55
UB Ratio	0.991	0.958	0.972	0.983	0.988
30-nodes					
# of arcs	168	195	226	49	76
L2 (km.)	10	10	8	23	19
# Solved	9	9	9	9	9
CPU (sec.)	202.8	347.7	357	2.8	35.8
UB Ratio	0.936	0.954	0.92	0.986	0.957
40-nodes					
# of arcs	142	242	353	163	81
L2 (km.)	15	10	8	14	23
# Solved	9	7	7	9	9
CPU (min.)	19.7	48.84	63.43	32.24	5.01
UB Ratio	0.971	0.935	0.91	0.94	0.985
50-nodes					
# of arcs	464	125	89	200	267
L2 (km.)	9	23	36	15	11
# Solved	6	9	9	6	6
CPU (min.)	114	35.13	0.48	64.64	78.76
UB Ratio	0.929	0.972	0.989	0.939	0.958

Table 4: Summary of $|N| \leq 50$ problems

	(75,150) problems	(100,200) problems	(150,300) problems
# Solved	10	9	7
CPU (hr.)	0.95	2.03	1.9
UB Ratio	0.966	0.973	0.967

Table 5: Summary of the large-scale problems

The most challenging 150-node instance terminated after 5.05 hours. We also solved the same instance to optimality, which took 24.5 hours of CPU time. It is noteworthy that the gap between the solution at termination and the optimal solution is only 0.8%. Our analysis of the non-terminated instances showed that the optimal solution is often reached fairly early in Branch and Bound, whereas its validation can be time-consuming. These results indicate that the proposed algorithm can also serve as an efficient heuristic.

During the course of the computational experiments, we also tested alternative strategies for branching and bounding. However, they did not improve computational efficiency. Thus, we conclude that the methodology described in Section 3 can be used for solving real-life problems.

5 The Quebec-Ontario Problem

In this section, we study the emergency response infrastructure for gasoline incidents on the highway networks of Quebec and Ontario in Canada. Our aim is to provide an assessment of the coverage provided by the current system and to demosntrate the improvement that can be achieved via the proposed methodology. Verter and Kara (2001) showed that Geographical Information Systems (GIS) are essential means for large-scale risk assessment endeavors. Thus, we derived the model parameters from a GIS-based representation of the two Provinces. We used ArcView 3.1 GIS software to superpose three layers of digital maps: the population zones, the road network and the origin-destination points for each shipment. This enabled us to estimate the route choices of hazmat carriers and the resulting level of population exposure around each highway link. The coverage provided by each alternative response team station was also determined via the GIS-based representation.

The data set for this application is compiled from a number of sources. Statistics Canada keeps a record of each hazmat shipment including its origin, destination, type of material, number of truck-loads and monetary value. These records indicate that 102,420 truck-loads of gasoline were carried between 251 origin-destination pairs in 1998. Transport Canada(2000) requires evacuation of the people residing within 800 meters of a gasoline spill. We obtained population data from the 1996 census, which contains 1149 sub-divisions in Quebec and 543 sub-divisions in Ontario. Most of these zones have very low population density. Thus, our model includes only those census sub-divisions with population density higher than 40 people/km^2. This amounts to 108 zones in Quebec with a total population of 3.8 million and 72 zones in Ontario with a total population of 7.6 million. Our highway network model is based on the ArcView 3.1 map and it has 205 arcs and 176 nodes. An arc corresponds to an urban road if it lies within a population center and it is considered a rural road otherwise. We assume that response teams travel 50 km/hour on urban roads and 90 km/h on rural roads. These average travel speeds translate coverage distances to response times.

In order to derive problem parameters, we assume that hazmat carriers use the shortest path for each shipment. This allows us to estimate the number of gasoline trucks on each highway link. Through GIS, we also determine the number of people living within 800 meters of each link. The multiplication of these two numbers for a highway link gives the total population exposure (in truck-people), which we use as a proxy of the benefit of providing full coverage to the link i.e., w_{ij}. Interestingly, only 95 of the 205 arcs have $w_{ij} > 0$ in this instance, and w_{ij} has a large range of values. We avoid potential stability problems during the solution process by normalizing arc weights in the model i.e., we divide each w_{ij} by $\max_{ij} w_{ij}$. The highway link with maximum population exposure is in Toronto. The total benefit of covering all the 95 arcs with $w_{ij} > 0$ is 5.0513, which we use as a benchmark.

There are 23 gasoline shipment origins in Quebec and Ontario with a wide range of activity levels. Four of these origins account for 78% of the 102,420 shipments[8], whereas three origins ship less than 50 gasoline trucks annually. The major shipment origins in the two Provinces are depicted in Figure 4. As mentioned in section 1, hazmat shippers

[8]Toronto 30,440 trucks, La Cote de Beupre 28,561 trucks, Laval(North of Montreal) 10,758 trucks and Brant County 10,577 trucks.

Response Time	Current 20-Team	Proposed 20-Team	Proposed 14-Team
30 min.	59.8	96.7	96.7
60 min.	92.2	98.1	97.5
90 min.	98.0	99.9	99.9

Table 6: Coverage percentages for the Quebec-Ontario problem

in Canada are responsible from emegencies during transport. Most major shippers, such as Shell, PetroCanada and Ultramar, employ their own specialized response team, whereas small-scale shippers often outsource their ERAP to a third party. Thus, we represent the existing emergency response network via a response team station at each shipment origin, except the three smallest sites. Our calculations indicate that the current 20-team system requires more than 1.5 hours to provide full coverage. More specifically, the total coverage within 90 minutes is 4.9507, which amounts to 98% of the benchmark.

----------Insert Figure 4 here----------

The current specialized response team locations certainly provide convenience in stationing the teams and their equipment. Intuitively, however, the shipment origins are not necessarily the best sites for maximizing coverage to possible road incidents. We used the proposed model to determine the extent of improvement in response times that can be achieved via optimizing the emergency network design. To facilitate the analysis, we solved the problem for response times of 30 minutes, 60 minutes and 90 minutes. Under a limit of 400,000 Branch and Bound nodes, each of the three instances took around 20 hours before termination. Table 6 provides a comparison of the coverage provided by the current and proposed response networks. Note that the proposed 20-team network covers 97% of the highway network within 30 minutes, whereas the current system needs about 90 minutes to provide the same coverage. In other words, it is possible to achieve a remarkable 67% reduction in the response times to gasoline incidents by optimizing location of the 20 response teams.

Re-location of response team stations requires a capital outlay, which may be excessive

for small-scale shippers. Therefore, in re-designing the emergency response network, we focus on the shipments that involve more than 1,000 truck-loads of gasoline annually. There are 14 such shipment origins, and hence Table 6 also depicts the coverage statistics for the proposed 14-team network. Interestingly, the percent coverage remains almost at the same level despite the 30 % reduction in the number of response teams. We were able to solve the 14-team problem with 30 minutes response time to optimality in about 50 hours. The optimal solution provides 97.9% coverage i.e., the solution at termination is within 1% of the best solution for this instance. More importantly, only two of the 14 teams are located at their current site in the optimal solution.

Provincial governments of Quebec and Ontario have jurisdiction over highway shipments of dangerous goods. The above analysis, however, adopts a holistic approach in modeling the highway networks of the two Provinces as a single entity. There are obvious challenges associated with the implementation of such a multi-Province solution. In order to determine benefits of the holistic approach, we also optimized each Province's response network in isolation. Currently, there are 5 response statios in Quebec and 15 stations in Ontario. For a response time of 30 minutes, the maximum coverage of the 5-team network in Quebec is 1.7 and that of the 15-team network in Ontario is 3.19. Thus, the total coverage provided in the two Provinces is 4.89, which is equal to the coverage provided by the holistic approach (i.e., 96.7 % of the benchmark as depicted in Table 6). The additional coverage provided by streamlining the Provincial networks is also marginal for response times of 60 and 90 minutes. Consequently, the time and effort required for coordinating the emergency response network re-design processes in the two Provinces would be hard to justify.

6 Concluding Comments

Time is of essence in responding to hazmat incidents. Quick arrival of a specialized team at the incident site can reduce the undesirable impact considerably. Response time depends on the distance between the specialized team station and the incident site. Therefore, the locations of response team stations consitute a major factor in the design of an emergency response network for dangerous goods incidents in a region. In this paper, we present the

maximal arc-covering location model as a means to optimize the structure of an emergency response network. We outline a novel solution method and demonstrate its efficiency on randomly generated problem instances. An application of the proposed methodology in Quebec and Ontario pointed out the possibility of a significant improvement in response capability via relocation of the existing stations. Naturally, the implementation phase requires an agreement between the provincial governments and the hazmat shippers with regards to the allotment of relocation costs.

The likelihood that a response team will be busy at the time of an incident has attracted considerable attention in the maximal covering literature since the seminal work of Daskin (1983). Given the very low probabilities associated hazmat incidents, however, the occurrence of multiple accidents within the response area of a specialized team is highly unlikely. Therefore, in the context of hazmat transportation, we can safely assume that the response teams will be available at all times.

The notion of gradual covering decay, recently proposed by Berman et al. (2003), provides a promising avenue for future research. In this paper, we followed the traditional approach in considering a potential accident site "uncovered", if a reponse team cannot reach to this point within the threshold time. In responding to a hazmat incident, however, a specialized team can still mitigate some of the impact despite arriving after the threshold time. The incorporation of gradual covering decay requires the use of a dynamic transport risk model that accounts for the time distribution of undesirable consequences.

Finally, the government can certainly prohibit the use of "uncovered" road links by hazmat trucks. Kara and Verter (2002) developed a model to determine the road segments that should be closed to hazmat shipments so as to minize the total transport risk in a region. The integration of their model with the model proposed in this paper is non-trivial from a solution methodology perspective. Nonetheless, it would be an important step toward the development of a comprehensive transport risk mitigation policy.

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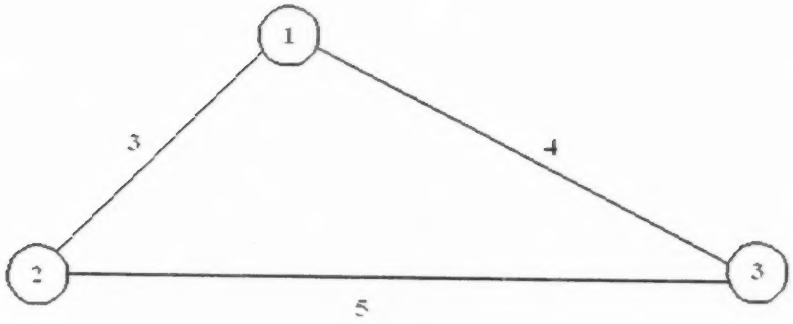

Figure 1: A 3-Node Network

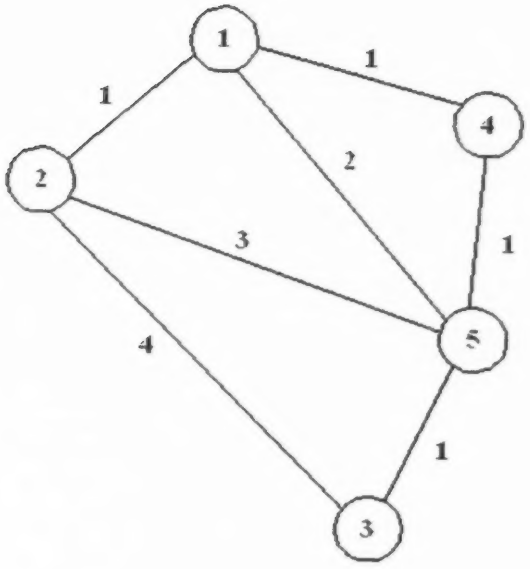

Figure 2: A 5-Node Network

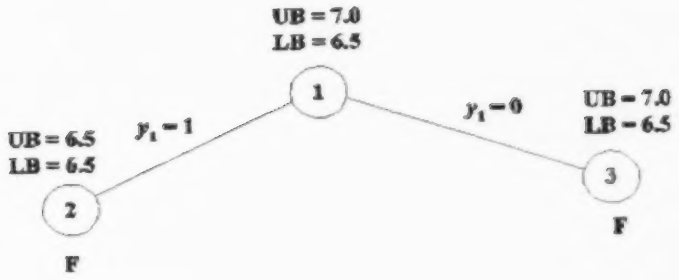

Figure 3: The Branch and Bound Tree for the Example

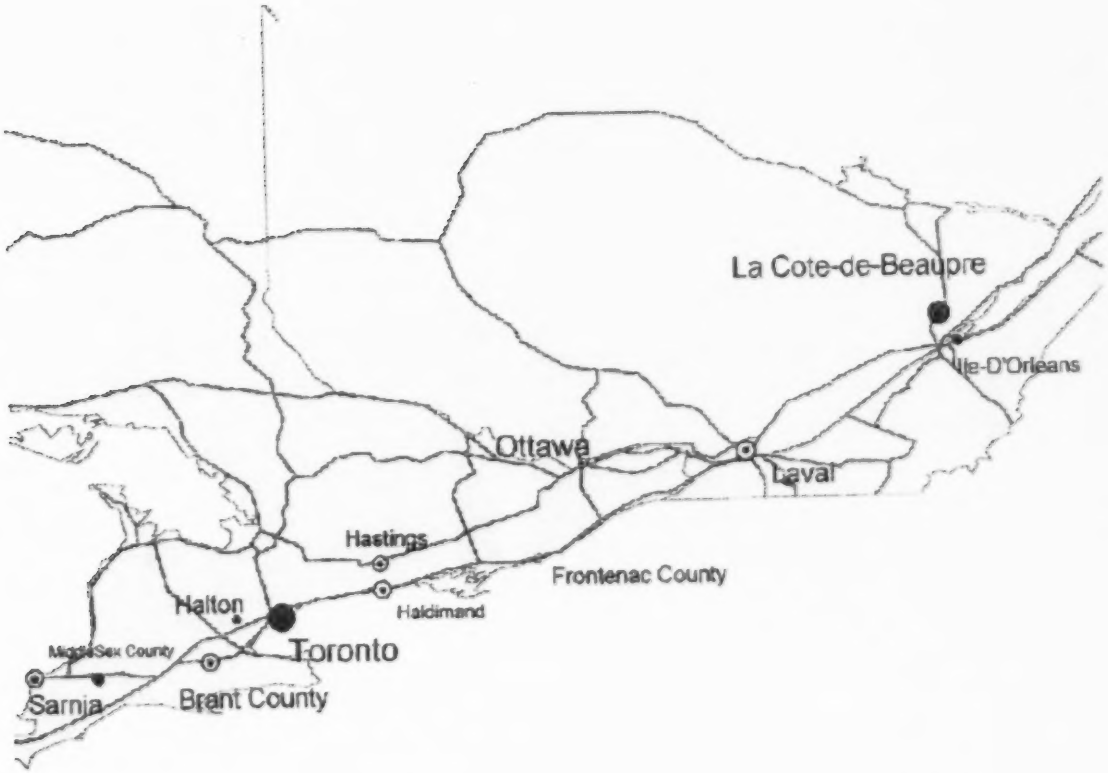

Figure 4: Origins of Major Gasoline Shipments (size of circular points is proportional to the annual amount of shipment)